## RESOURCE PROSPECTOR PROPULSION COLD FLOW TEST

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### ABSTRACT

For the past year, NASA Marshall Space Flight Center and Johnson Space Center have been working on a government version of a lunar lander design for the Resource Prospector Mission. A propulsion cold flow test system, representing an early flight design of the propulsion system, has been fabricated and integrated to a prototype lander structure at Marshall Space Flight Center. The primary objective of the cold flow test is to simulate the Resource Prospector propulsion system operation through water flow testing and obtain data for anchoring analytical models. This effort will also provide an opportunity to develop a propulsion system mockup to examine hardware integration to a flight structure. This paper will report the work progress of the propulsion cold flow test system development and test preparation. At the time this paper is written, the initial waterhammer testing is underway. The initial assessment of the test data suggests that the results are as expected and have a similar trend with the pretest prediction. The test results will be reported in a future conference.

### INTRODUCTION

NASA's Resource Prospector (RP) Mission to the Moon brings together the lander development efforts under the Science Mission and Human Exploration Mission Directorates. The RP mission consists of a pallet lander, a rover, and a science instrumentation package containing a miniature drilling and chemistry plant to collect and analyze soil for volatile components such as water or hydrogen that could be used in human exploration efforts[1]. The mission is being led by NASA Ames Research Center; while Marshall Space Flight Center (MSFC) and Johnson Space Center (JSC) are working on the design of a government-version lander. A major sub-subsystem of the lander will be the propulsion system, which will provide thrust to perform in-flight guidance navigation and control (GNC) required from the time the spacecraft separates from the launch vehicle until touchdown on the lunar surface. After trans-lunar injection, the lander propulsion system will maintain the trajectory with correction maneuvers, control spacecraft attitude, provide a high-thrust prior to the landing to match lunar surface velocity, and perform terminal descent to the lunar surface. To accomplish these functions, the government version of the lander design has two stages: a separable solid stage for the braking function and a bi-propellant, pressure-regulated, pulsing liquid stage to perform all other functions. The concept of the lander is shown in Figure 1. The solid stage is the primary provider of deltaV. In the current reference configuration, the solid stage provides 15,000-lbf of thrust with a single burn of ~ 80's seconds.

The flow schematic and design layout of the liquid propulsion for this lander are presented in Figures 2 and 3, respectively. Hypergolic propellants monomethylhydrazine (MMH) and nitrogen tetroxide (NTO) will be used to fuel sixteen 70-lbf class descent thrusters and twelve 5-lbf attitude control thrusters. These thrusters are grouped into four thruster modules that are located on corners of the lander. All thrusters will operate with pulsing modes for precision and soft landing. The descent thrusters will provide main thrust for trajectory correction maneuvers and terminal descent,while the ACS thrusters will perform pitch, roll, yaw, and nutation damping. The current projected requirements of the descent and ACS thruster systems are summarized in Table 1 below.

Table 1: Projected requirements of the liquid propulsion system for the lander stage[2]

| Requirement Parameters | Descent thrusters | Attitude Control Thrusters |
|---|---|---|
| Thrust Class (lbf) | 70 | 5 |
| Minimum Impulse Bit (lbf-sec) | 2.8 | 0.6 |
| Total impulse delivered (lbf-sec) | $145 \times 10^3$ | $7.9 \times 10^3$ |
| Propellant consumption (lbm) | 557 | 28 |

With respect to the propellant storage and distribution system, four metal diaphragm tanks, two connected-in-parallel tanks per propellant component, will be used along with a high-pressure composite overwrapped pressure vessel (COPV) for the helium pressurant gas. The metal diaphragm tanks offer the advantage of active propellant control to eliminate technical issues, such as propellant slosh and gaseous pressurant entrainment to the engines, while gaining high propellant expulsion efficiency (~98%). Many of the major propulsion system components are heritage Intercontinental Ballistic Missile (ICBM) Peacekeeper (PK) hardware obtained by NASA from the Air Force. Using government available PK propulsion components along with some commercial off-the-shelf (COTS) hardware would significantly reduce the cost of the spacecraft while maintaining the technical and schedule risk at a minimal level.

## OBJECTIVES OF PROPULSION COLD FLOW TEST

In parallel with the flight system design activities, a simulated propulsion system based on the drawings of the early flight design was built to evaluate the feasibility of using available PK and COTS propulsion components in the lander application. This buildup also serves as a mockup for demonstrating the integration of a propulsion system to a flight-like lander structure. The propulsion cold flow test will provide data to characterize the steady state flow and pressure conditions as well as transient behavior. The testing will include a focused parametric study (variations in operating conditions, simulated variations in metal diaphragm pressure drops, etc.) on steady state operation, slump and waterhammer effects due to the combination of opening and closing of the thruster valves, and system priming (initial system activation). Additional repeated tests will be performed to assess the flight hardware integrity (4 x life cycles) including its ability to satisfy the safety margins. In summary, the test effort is laid out to achieve the following objectives:

- Obtain parametric test data to characterize the propulsion system during the transient (waterhammer, fluid system slump), steady state pressure distribution on the feed line system.
- Obtain test data for anchoring analytical models of the propulsion fluid system in support of flight design and flight prediction.
- Verify operational performance and hardware integrity (cycle life, functional, etc.) of flight propulsion components used in the test setup.
- Serve as a propulsion system mockup to evaluate the physical and dynamic interfaces with other sub-systems, specifically the structure and thermal.
- Serve as a propulsion system mockup to demonstrate, gain knowledge, and practice the propulsion integration procedures.

## DESCRIPTION OF THE PROPULSION COLD FLOW TEST SYSTEM

The propulsion cold flow test system was fabricated based on the early design of the flight system. The propulsion components and feed lines were integrated into a preliminary prototype lander structure which was fabricated and assembled in paralled with the propulsion

system buildup. The integration of the propulsion system to the lander structure, as shown in Figure 4, was performed in a high bay facility at MSFC, building 4205.

Dimensions of the lander structure are roughly 10-ft by 10-ft. The flight drawings at the time were utilized to build-up the propulsion cold flow test system. Though the flight drawings were used, deviations occurred based on cost constraints, schedule constraints including component availability, producibility, and test considerations.

The flow schematic of the propulsion cold flow test setup is depicted in Figure 5. Fuel and oxidizer feed line circuits are shown in red and green, respectively, while the pressurization system is in blue. To simulate the descent thrusters, the PK thruster valves are used with an orifice downstream of each valve to simulate the back pressure of the thruster chamber. Since ACS thruster valves are not available for cold flow testing, the propellant lines for the thrusters are capped at the ends. It should be noted that the ACS thrusters would utilize a small quantity of propellants as compared with the propellants consumed of the descent thrusters; therefore, excluding the ACS thruster valves on the test setup will not significantly alter the waterhammer effects.

For the cold flow test setup, considerable instrumentation was incorporated and strategically placed throughout the feed line system to capture the transient behavior and surge pressure due the waterhammer and system priming. The pressure transducers were installed at thruster valve inlets within the thruster modules, as well as at the ends of the propellant service lines near the service valve locations. For the thruster valves, the currents and voltages of the valves are also recorded to monitor the valve health and assess the valve opening/closing response times. This data will be useful in assessing these components' operation specifications and qualifications versus the actual conditions. Temperature readings on the pressurization system and tanks are also collected during test..

## FLUID SYSTEMS FOR THE COLD FLOW TEST

To avoid the high cost of using the metal-diaphragm tanks for the cold flow tests, Department-of-Transportation (DOT) rated COPV tanks are being used. The pressure drop across the metal diaphragm is simulated by adding flow resistance to an orifice at each of the tank outlets. The two tanks for each are connected together with a manifold to create a distributed feed system for each of the four thruster modules. Hand operated isolation valves are incorporated at the tank outlets as a way to isolate each of the tanks from the feed system during certain pre- and post-test operations.

The propellant feed system also includes the ability to install a burst disk into the system. The burst disk will be installed within the lines for the priming tests as a way to simulate the pyro valve in the flight system. A relief valve is not incorporated in the propellant feed systems since the compliance of the relief valve would impact the system surge pressure.

Deionized water is used as a simulant for both the fuel and oxidizer. For the test runs, the mass flow rates of simulants are matched with actual propellant flow rates for individual propellant components. Other parameters, such as density, viscosity, pressure, etc. will be evaluated for anchoring the model. The incompressibility of water better approximates MMH, and water will produce surge pressures slightly higher than the propellants and is therefore conservative.

The propulsion cold flow test system includes several different pressurization options. Each of these options will be exercised during the course of testing to provide the most efficient and cost effective way of collecting data. Nitrogen is used as the pressurant gas on most tests and is supplied through a facility regulator panel that ties into a service line just of upstream of the propellant tanks. During operation of the test article with nitrogen, the high-pressure system on the test article is not used and is isolated from the rest of the test article. Helium pressurant will be required for PK pressure regulator performance testing and conceptual usage profile testing. For the cold flow test setup, relief valves are incorporated into the pressurization system to

protect the COPV, the PK regulator, and the low-pressure system downstream of the PK regulator in the event the regulator fails open.

## TEST SERIES FORMULATION

The RP propulsion system on the lander stage is complex. It is composed of widely-distributed feed line systems to fuel twenty eight thrusters that operate in pulse modes for the spacecraft attitude control and soft and precision landing. Although the system utilizes metal-diaphragm tanks for the active propellant control, connecting them in parallel may create unwanted propellant differential drainage. To investigate such a complex feed line system, tests have been carefully formulated to address most propulsion operation aspects. One of the goals for this test effort is to identify propulsion system operational constraints for GNC. Test conditions and valve pulsing commands will be ordered from low to high risks to avoid damaging hardware when testing. The outcome of such test series may also lead to future system design improvement. The types of tests on the propulsion cold flow test system are outlined on Table 2 below. Details of the specific thruster valve operation sequences are included in the test matrix which will be discussed in the future report.

Table 2: Outline of test series to be performed on the propulsion cold flow system.

| Test Series | Test Description |
|---|---|
| *Waterhammer / Slump* | This test series will consist of single and multiple-thruster waterhammer tests. Since surge and slump pressures will be expected during flight when opening and closing thruster valves, this test series will address the system dynamic response to the operation of individual thrusters and sets of thrusters. The results will also provide guidance to GNC on propulsion system operational constraints. |
| *System Priming* | Depending on the initial pressure conditions of the propellant tank and the feed lines, the initial activation of the propulsion system, also called as system priming, perhaps generates one of the highest transient pressures that the flight system will experience. This is due to the fact that the feed line downstream of the pyro isolation valve is at a near-vacuum condition. When the valve is activated, the propellants at the tank pressure fill up the feed lines at a rapid rate and produce a high surge pressure throughout the feed systemTo simulate the priming of the propellant feed lines, the thruster valves will be removed and the feed lines capped to avoid possible valve damage. A burst disk will be installed at the location where the pyro valve would be in the flight system. The lines will then be evacuated. At this point the tank pressure will be slowly ramped up until the burst disk fails simulating pyrotechnic valve operation and feed system priming. |
| *Differential Draining* | The metal diaphragm tanks used on the actual flight system may have some variations in the pressure drop across the diaphragm due to the diaphragm manufacturing tolerance. Since the tanks are connected in a parallel fashion, a potential propellant differential drainage may exist especially near the end of the operation. In the flight system, an orifice is placed downstream of each propellant tank to minimize this differential draining. The results from this test series will aid in sizing the orifice appropriately. For the test setup, orifices with small delta P differences will be installed in each propellant system, the tanks filled with water, pressurized, and allowed to drain. The draining rates and propellant imbalances between tanks will then be evaluated. |
| *Representative Conceptual Usage Profile* | To provide integrated information for aiding GNC in development of the mission profiles, conceptual usage profile tests will be performed in the later part of the test series. This test sequence will use the PK regulator with |

| | |
|---|---|
| | helium for pressurization. |
| *Regulator Slam Start and Ullage Sensitivity* | This test series will focus on evaluating the sensitivity of the PK regulator performance with various initial ullage volumes in the propellant tanks. This testing will be completed with the helium loaded in the pressurant COPV and with water loaded in the DOT propellant COPVs. A subset of this test sequence may include the incorporation of a burst disk upstream of the regulator to simulate the helium pyro valve. |
| *Propulsion component life cycle* | The test series will be dedicated to demonstrating 4x cycle life for satisfying the structural integrity for the RP operations. Based on the current anticipated flight mission, some of the propulsion components may be operated with conditions that exceed the initial qualification level. To minimize the chance of having to requalify this hardware, additional cycles are being completed as rationale to support verification closure. This test series will actually repeat test sequences required for other test types to achieve the additional valve sequences. This testing will also help to acquire some repeatability data. |

## THE CURRENT STATUS OF THE COLD FLOW TEST

At the time this paper is written, the propulsion cold flow test system is configured with the nitrogen pressurant supplied by the facility regulator panel. Leak checks for the entire system with water were performed. To reduce gas trapped in the feed lines, a vacuum pump was used to evacuate the line systems downstream of the propellant tank isolation valves prior to the water loading. The trapped gas was also bled out at high point vents on the feed lines and at the end caps of the ACS thruster lines. It should be noted that a set of metal tanks that have a similar configuration to the flight tanks were also fabricated and installed to the cold flow system for cold flow test demonstrations. Several initial tests have successfully been conducted for the system check-out with both COPV and metal tanks. The initial assessment of the test data suggests that the results are expected and they have similar trends with the pre-test predictions. Additional review of the test data is being conducted at this time. The next step is to complete integration of the remainder of the high-pressure pressurization system to the cold flow test system for future testing.

## SUMMARY AND CONCLUSIONS

On the government version of the lander for the Resource Prospector mission, the liquid propulsion system consists of a complex feed line network for delivering propellants to thrusters that are located at corners of the large-size (10’x10’) lander structure. The thrusters will operate in pulse mode to perform spacecraft attitude control, trajectory correction maneuvers, as well as to provide a capability for soft and precision landing. Consequently, the fluid flow transient behavior, especially high surge pressures due to the system priming and waterhammer are of great concern in the design for such a complex propulsion system. Moreover, the flight system will be built from existing components, whose specification and qualification have been for previous applications. The goal is to use them within their qualification as much as possible for reducing the development cost. Hence, the propulsion system cold flow tests will be crucial for gaining knowledge on the system operation aspects, fluid system transient characteristics, and also for identifying potential technical issues. The early-test approach will provide an opportunity to implement design improvements while the propulsion system development is still in progress. The test data will not only be valuable for anchoring the system fluid flow models that will be used for the flight predictions, but also for providing GNC guidance on the propulsion system operational constraints.

Significant progress in the test setup has been made. The fabrication and integration of the propulsion cold flow system is completed and ready for conducting tests. The system is highly instrumented to capture the steady-state and transient behaviors of the fluid system. The test series and valve sequences are carefully formulated to address most possible operational aspects of the RP mission. Although not all actual flight components, such as pyro valves, metal-diaphragm tanks, and ACS thruster valves, etc., are utilized in the cold flow configuration due to the nature of the cold flow testing and their unavailability, the outcome of the test activities will still provide valuable data and information to accomplish the test objectives.

The initial checkout tests have been conducted. The results suggest that the test data have been similar to the pre-test predictions. The test efforts will yield valuable test data and be instrumental to positively impact the propulsion system development process.

## ACKNOWLEDGMENTS

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## REFERENCES

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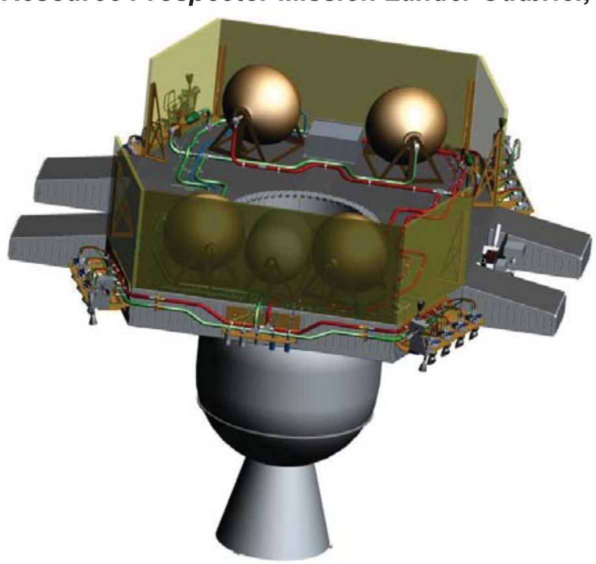

**Figure 1: Government version of RP lander. SRM for braking stage and a bi-prop system for lander stage.**

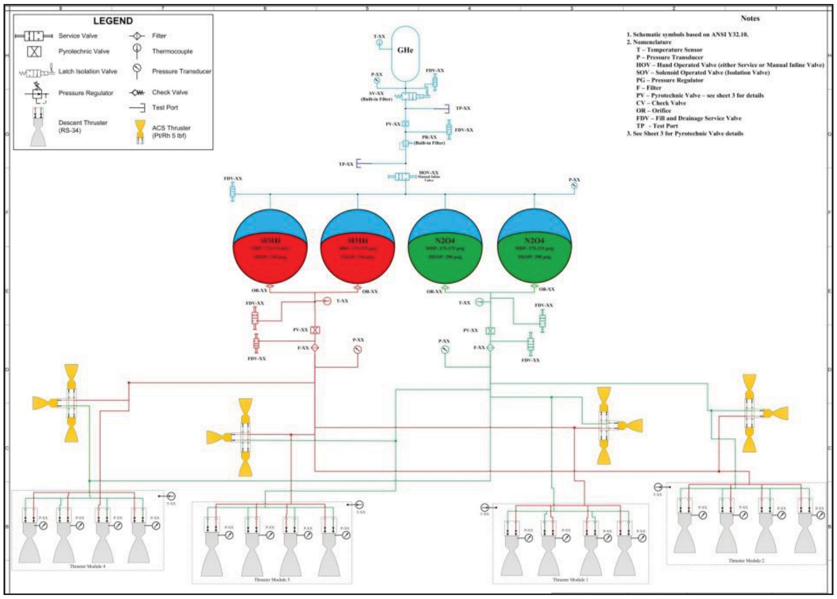


**Figure 2: Flow schematic of liquid propulsion for lander stage**

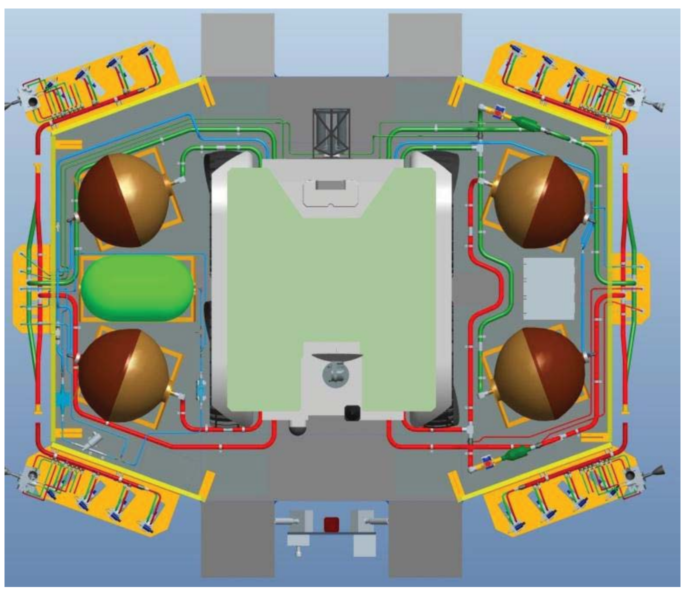

**Figure 3: Layout design of liquid propulsion system**

**Figure 4: Completion of propulsion cold flow test system integration to lander structure**

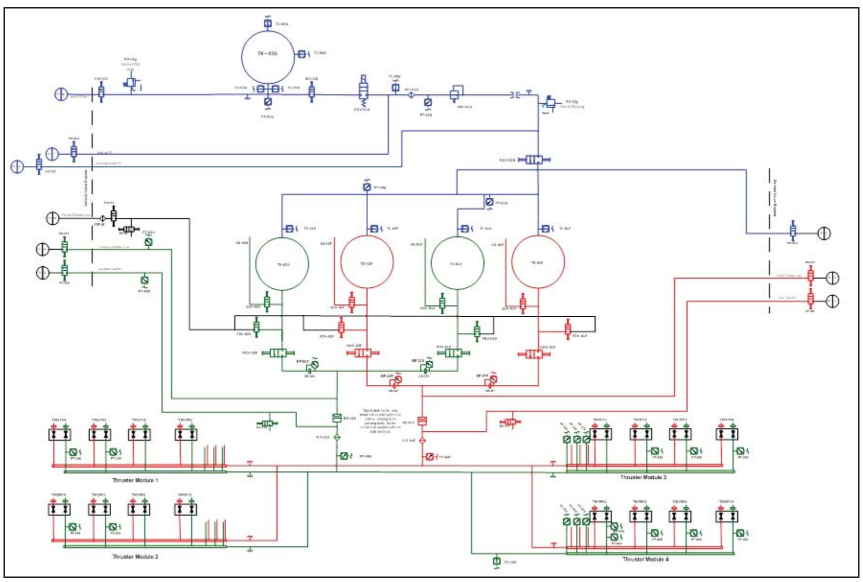


**Figure 5: Flow schematic of propulsion cold flow test system setup**